Physics 262

Lab #1: Lock-In Amplifier

John Yamrick

Abstract

This lab studied the workings of a photodiode and lock-in amplifier. The linearity and frequency response of the photodiode were examined.

Introduction

The purpose of this experiment was to gain experience with the operation of a lock-in amplifier. A periodic signal was sent via the beam of a He-Ne laser and picked up by a photo-detector. The amplitude of the signal could be observed using a lock-in amplifier. The lock-in was then used to determine the range of intensities for which the photo-detector operated linearly as well as the frequency response of the system.

Theoretical Background

A lock-in amplifier is a device used to measure voltage signals with amplitudes significantly less than the ambient noise. They do this by multiplying the input signal by a reference signal of the desired frequency. This creates a multitude of harmonic frequencies for each component of the input signal. For example, if a sinusoidal input signal at frequency f_{input} were multiplied by a sinusoidal reference signal at frequency f_{ref} the result would be a pair of new sinusoids at $(f_{input} + f_{ref} + \phi)$ and $(f_{input} - f_{ref} + \phi)$, where ϕ is the phase difference between the signals. In a lock-in, the desired reference frequency is fed to the device as f_{ref} and the input signal consists of the desired signal as well as noise signals at all possible frequencies. In typical applications, the magnitude of the noise signals is significantly larger than that of the target signal.

In the special case where the desired signal is multiplied by the reference signal, f_{input} and f_{ref} are the same, $\cos(f_{input} - f_{ref} + \phi) = \cos(\phi)$, and a DC component is created. Only the target frequency, when multiplied by the reference frequency, will produce a DC result. Its amplitude will be a function of the phase between input and reference signals, as well as the amplitude of the input signal. If the phase is adjusted to 90°, then the DC result is directly proportional to the amplitude of the desired signal. A simple low-pass filter can be designed to throw away all frequencies other than DC. This method can provide a reliable measure of the signal power even in the face of excessive noise. Because it relies on analysis of the phase difference between the target and reference signals, it is termed phase-sensitive detection.

Another term used in reference to lock-In amplifiers is dynamic reserve. This is a ratio of the amount of noise that the lock-in can tolerate relative to the smallest decipherable signal. Higher dynamic reserve is obviously better in terms of signal clarity, but can put a lot of strain on the input-stage amplifier. If the pre-amplifier is pushed beyond its capabilities, the lock-in will go into an overload fault to avoid damaging the device. Lock-in dynamic reserve is highly frequency dependent (as any noise at the target frequency will be passed through in entirety) and so many lock-ins have an adjustable dynamic reserve that can be used to maximize signal clarity without overloading.

Lock-ins, like many electronic measurement devices, often give the user access to the time constants used when acquiring data. Here, time constant refers to the amount of time spent averaging the signal before a reading is displayed. Lengthening the time constant will provide smoother data, but risks losing track of any sudden effects. Users should have an idea of the time intervals over which they might expect to see a significant effect and should set the time constant so that it is no longer than this interval. If they have no idea, it might be best to experiment with a few different time constants to see what effects can be observed.

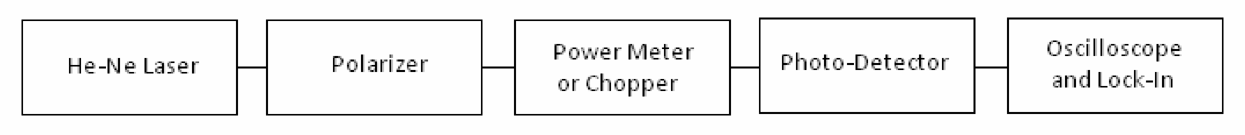
Experimental Procedure

Apparatus

Polarized He-Ne Laser, Chopper, Adjustable Polarizer, Optical Power Meter, Photodiode, Oscilloscope, Lock-In Amplifier

Procedure

The apparatus was arranged in the following manner, with the position of the chopper and power meter being exchanged at various point in the experiment depending on whether beam intensity or a periodic signal were required.



The first goal of the lab was to determine the linear region of the photo-detector with regards to laser intensity. At a certain point the photo-detector will saturate and small fluctuations will become imperceptible. It was necessary to tone down the intensity of the laser in order to collect any meaningful data on the frequency response later in the experiment. It was also helpful to diffuse the beam slightly before it entered the photo-detector. This reduced the intensity of the beam actually hitting the photo-detector, thus increasing the range of incident intensities which would produce linear behavior and the precision with which these intensities could be selected. Diffusion was achieved with a simple piece of scotch tape placed over the front of the photo-detector.

The linear region was determined by taking power measurements with the optical power meter and comparing these values with the output of the photo-detector as seen on the oscilloscope. Since the laser used in this experiment was polarized, various beam intensities could be achieved by adjusting an external polarizer in front of the beam to admit more or less light (polarized light passing through another polarizer is attenuated based upon the difference in angle between the two axes of polarization). Dividing the output voltage by the power input provided a scale factor that would remain constant when inside the linear region. Note: In the block diagram above, the power meter blocks the path of the laser beam to the photo-detector and has to be removed and replaced between data points.

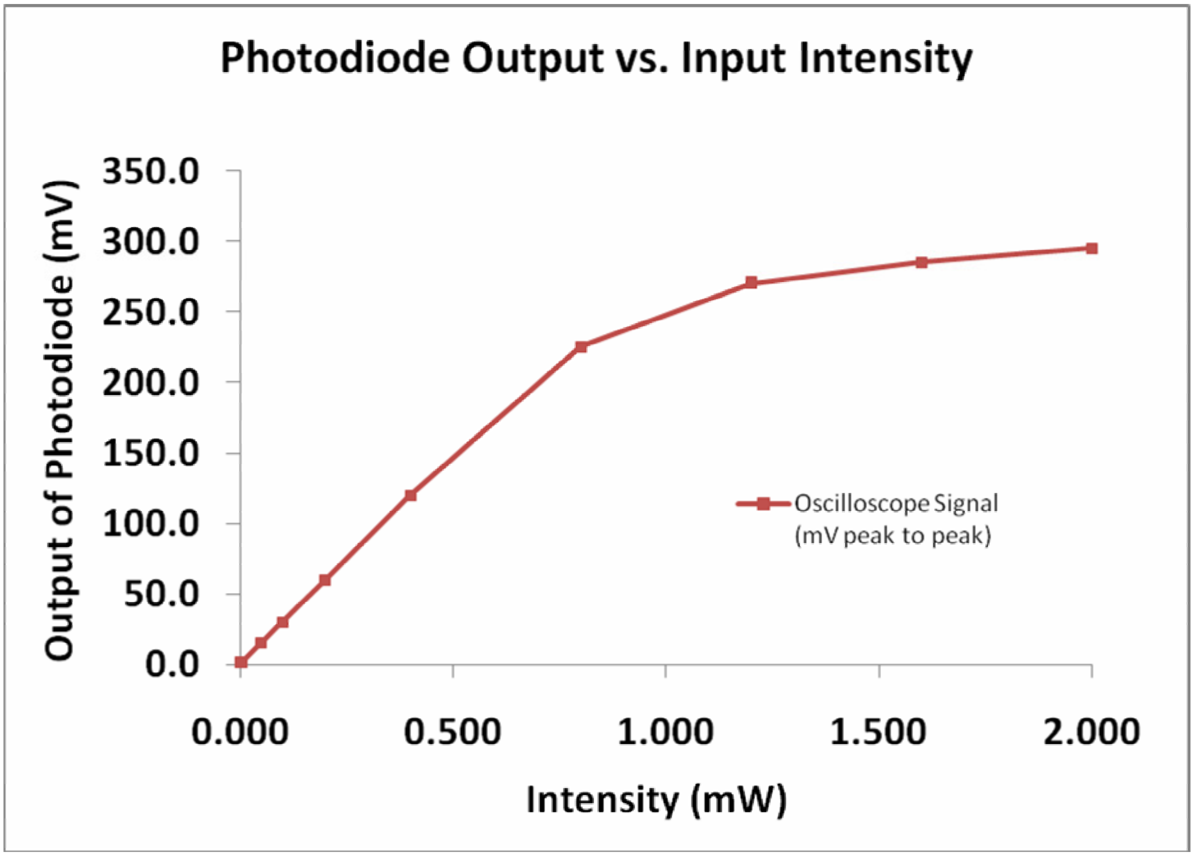
The next part of the experiment was to observe the frequency response of the photodiode. A set optical power within the linear range was decided upon and the chopper was installed in place of the optical power meter. Output was observed on both the oscilloscope and the lock-in amplifier as the frequency of the chopper was changed with an external knob.

The final experiment was to determine whether the frequency response of the photodiode had any dependence on intensity. This was achieved by re-installing the optical power meter and changing the intensity of the beam a second time by adjusting the polarizer. New frequency data were then taken at this intensity to spot check against previous measurements.

Experimental Results and Discussion

Below are the results illustrating range of intensity for linear operation of the photodiode:

Power Meter (mW)	Oscilloscope Signal (mV peak to peak)	Output / Input (mV/mW)
0.005	2.0	400
0.050	15.6	312
0.100	30.0	300
0.200	60.0	300
0.400	120	300
0.800	225	281
1.200	270	225
1.600	285	178
2.000	295	148

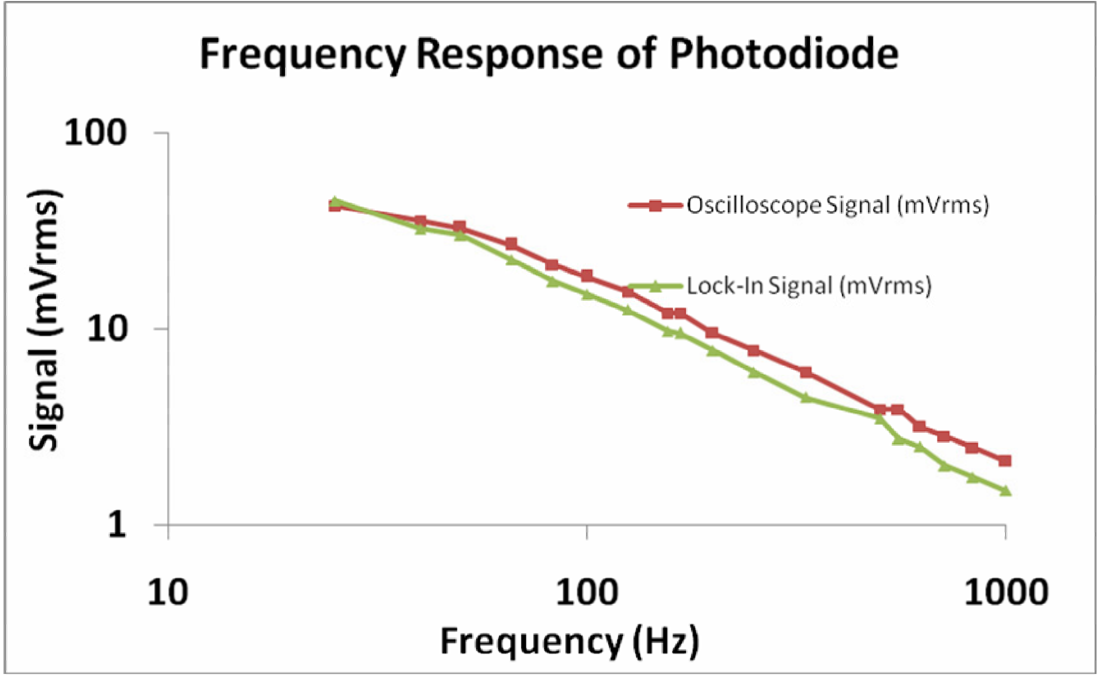


From both the graph and the table data, it is evident that the photodiode exhibits high linearity up to about 0.8 mW of input intensity, at which point it begins to saturate. To minimize the effects this non-linearity can have on the collected data, further measurements were taken at or below 0.400 mW intensity, well within the linear region of operation.

The next step was to use the lock-in amplifier to test the frequency response of the photodiode. Since the chopper intermittently interrupts the laser beam, the observed intensity would ideally be a square-wave where the troughs of the waveform correspond to ambient light and the peaks correspond to the sum of the laser intensity and the ambient light. In actuality, this square-wave was only observed up to a frequency of about 25 Hz. Beyond that, the square pulse takes on something of a sand-dune shape up until 125 Hz, were it stabilizes into a triangle wave as the photodiode tries to play catch-up to the repetitive changes in intensity.

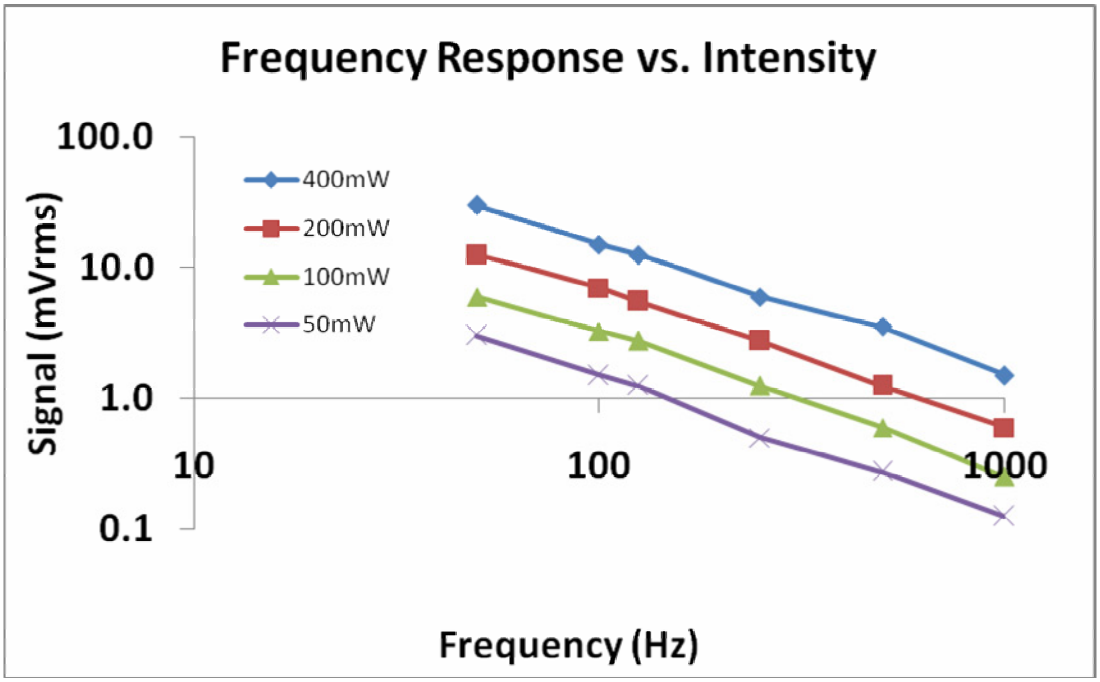
Below are the measured results for the signal voltage at an intensity of 0.400 mW:

Frequency (Hz)	Oscilloscope Signal (mV peak to peak)	Oscilloscope Signal (mVrms)	Lock-In Signal (mVrms)
25	120	42	45
40	100	35	32.5
50	92	33	30
66	76	27	22.5
83	60	21	17.5
100	52	18	15
125	44	16	12.5
156	34	12	9.75
167	34	12	9.5
200	27	9.5	7.75
250	22	7.8	6
333	17	6.0	4.5
500	11	3.9	3.5
555	11	3.9	2.75
625	9.0	3.2	2.5
714	8.0	2.8	2
833	7.0	2.5	1.75
1000	6.0	2.1	1.5



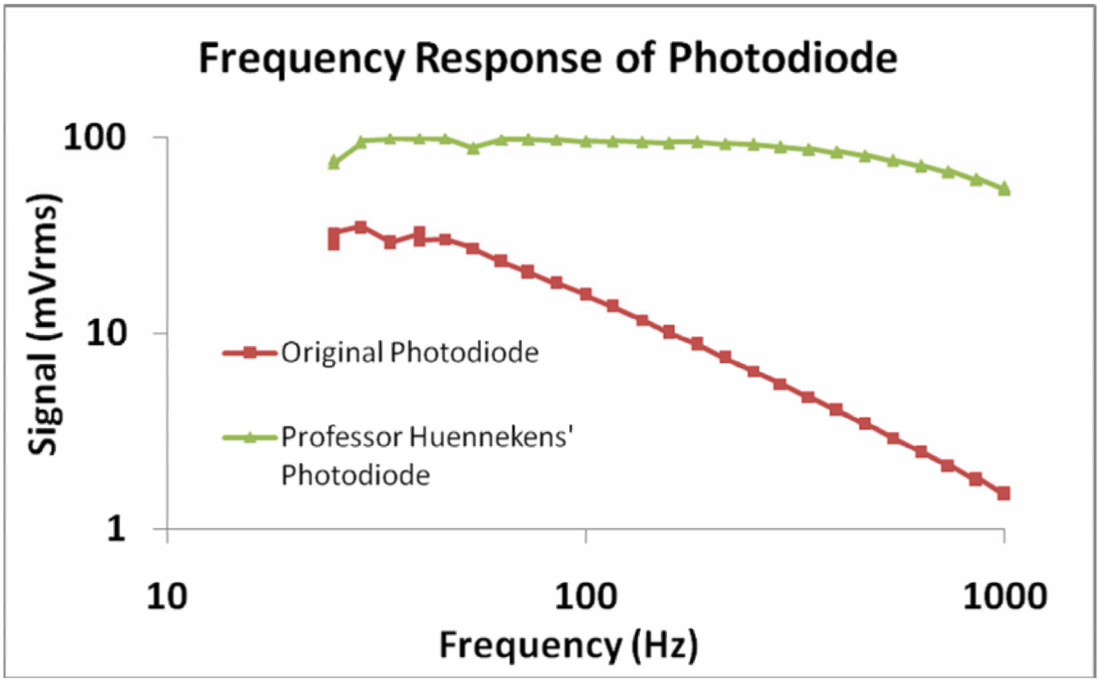
Another piece of data collected in this lab was to test whether the frequency response of the photodiode changed with laser intensity. The laser intensity was changed and data collected for several standard frequencies at each intensity. The results are compiled below:

	Lock-In Output (mVrms) at:			
Frequency	400mW	200mW	100mW	50mW
50	30.0	12.5	6.00	3.00
100	15.0	7.00	3.25	1.50
125	12.5	5.50	2.75	1.25
250	6.00	2.75	1.25	0.50
500	3.50	1.25	0.60	0.28
1000	1.50	0.60	0.25	0.13



Within each data series of intensity, the signal power seems to decrease by approximately the same ratio regardless of frequency. This means that the decreased signal power is a product merely of the intensity, and not of a combination of intensity and frequency response. Therefore it can be confirmed that the frequency response does not depend upon intensity of the laser beam.

As a final addendum to this lab, an additional round of frequency response data was collected using Labview programs to control the chopper and lock-in. Tests were conducted both on the original photo-diode used in the earlier parts of the experiment, and on another photo-diode supplied by Professor Huennekens. The results are plotted below.



Two possible explanations may describe the discrepancy between the curves. First, the new photo-diode may simply respond more quickly than the original one. In that case, data collected at 1000 Hz shows only the first part of the signal drop-off. As this old photo-diode was intentionally slowed to illustrate certain behaviors of the lock-in amplifier, this seems rational.

Another explanation is that the 0.400 mW beam intensity (determined to be well within the linear region of the original photo-diode) was too much for the new photo-diode and the device saturated. In that event, changes in frequency would have limited effects because the photo-diode is already being fully stimulated.

Summary

The photodiode was shown to exhibit linear detection of incoming optical energy up to an intensity of about 0.800 mW. Frequency response was shown over the full range of detectable chopper frequencies. The measured results from the oscilloscope and lock-in amplifier were compared. The frequency response was shown to be independent of beam intensity within the photodiode's linear range of operation. The original photodiode was compared to another using data collected with Labview software.